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EFFECT OF SHOT PEENING AND OVERLOAD RESIDUAL STRESSES ON EX35 MULTI-LUG BREECH FATIGUE LIFE

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13. ABSTRACT *(Maximum 200 words)*

The EX35 multi-lug breech system is designed to replace the conventional breech system in order to diffuse the concentrated load at the block-ring interface. This report describes the residual stress effect of shot peening and overload processes on the EX35 multi-lug breech fatigue life. Shot peening of the lugs utilized the inside diameter peening technique, and an overload cold working process was applied using an overload fixture. Residual stress distribution in the lugs was characterized using X-ray diffraction. The magnitude of the maximum compressive stresses induced by the two processes is comparable, while the overload process produces much deeper zones of compressive residual stresses than shot peening. Both shot peening and overload processes retard crack growth and improve fatigue life. Our analysis showed that the thicker layer of compressive residual stress generated by overload compared with the shot peening process improves the fatigue life of the multi-lug breeches by a factor of two.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

In the EX35 multi-lug breech design, a series of lugs replaces the conventional slide block breech to diffuse high-stress concentrations.[1] However, while stress concentrations can be reduced, they cannot be completely eliminated. In this study, cold working processes, such as shot peening and overload, were explored to induce favorable residual stresses in the lugs to counter high-tensile stresses during operation. The shot peening process increases resistance to fatigue failures and corrosion cracking. Shot peened residual stresses are generally monitored only by curvature determination in an Almen strip,[2,3] without X-ray diffraction analysis. Two papers summarize our investigation of shot peening and overload processes to induce favorable residual stresses in the multi-lug breech system:[4,5] The present paper summarizes the effect of shot peening and overload residual stresses on the fatigue life of EX35 breeches. Inside diameter shot peening residual stresses and preliminary overload residual stresses are presented. Another paper verifies the design of the EX35 multi-lug breech and compares experimental residual stress data with finite element modeling predictions of an EX35 multi-lug breech ring after overload.[5]

EX35 residual stress distribution in the lugs of shot peened and overloaded multi-lug breech rings was studied using two position-sensitive X-ray diffraction stress analyzers. Strain gages were attached to the fillets to measure hoop strains during the overload process and after the load was removed.[6] X-ray diffraction residual stress analysis in the lugs demonstrated that shot peened stresses at the bottom of the lugs were more uniformly distributed, while overload stresses were more directional and dependent on location and geometry. Maximum compressive residual stresses due to shot peening and overload processes are comparable in magnitude, but the plastic layer produced in the overload process is much deeper than the layer produced in the shot peening process in the areas of interest. Our analysis demonstrates that the thicker layer of compressive residual stresses generated by the overload process compared with the shot peening process improves the fatigue life of the multi-lug breech system by a factor of two.

EXPERIMENTAL PROCEDURE

Multi-Lug and Conventional Slide Block Breeches

Figure 1 presents a schematic diagram of the multi-lug breech ring/block assembly compared with a conventional breech. When chamber pressure is applied, strain gages attached in the fillets of the multi-lug breech experience tensile strains. The measured hoop strains in the conventional breech fillets are larger than the hoop strains in the multi-lug breech.[1] The approach to the multi-lug breech design emphasizes geometrical modification. Uniform pressure was applied to the breech block, which was transmitted to the breech ring through contacts at the fillets. The number of lugs, depth and geometry of the lugs, block/ring contact areas, contact interface angle, and distance between lugs were designed to diffuse stress concentrations and obtain optimized configuration of stress fields.

Shot Peening Process

To induce residual stress in the fillets of the multi-lug breech ring, shot peening and overload processes were explored. Two breech mechanisms, an upslider and a downslider, were tested. However, because the same design and machining techniques are used, no difference in stress distribution is expected. Two breeches, #18 and #21 (one upslider and one downslider, respectively), were shot peened. Two other breeches, #20 and #23 (one upslider and one downslider, respectively), were overloaded.

The multi-lug breech rings and blocks were shot peened by Hydro Honing Lab, East Hartford, CT, according to military specifications on shot peening.[7] Cast shots S-330 (0.84 mm or 33 mil) were used. In order to obtain uniform residual stresses in the fillets of the multi-lug ring, inside diameter peening as shown in Figure 2 was performed with custom-made 1/4" nozzle and 45° peening angle; air pressure was 70-80 psi; nozzle rotation was 90 to 100 rpm; and nozzle oscillation was full length of part at 30" per minute. In the multi-lug breech ring, all non-shot surfaces were masked, except areas inside the three lugs.

Overload Process

In the overload process, uniform pressure was applied to the breech block and transmitted to the breech ring through the contact regions. The overload process was performed by the Experimental Mechanics Branch of Benet Laboratories using an overload fixture.[6] Overload was achieved by a combination of hydraulic and mechanical forces. Hydraulic force was introduced by hydraulic fluid in the chamber, while mechanical force was achieved by area reduction of the breech end seal compared with the seal at the hydraulic fluid inlet end. The overload pressure applied at 50% overload was 1.5 times the design chamber pressure of 83 Ksi (580 MPa). The amount of overload was limited to avoid major changes in the contact region and depth of the gap from interfering in the breech operation.[6]

Fatigue Test and Fatigue-Failed Multi-Lug Breeches

In Figure 3, a multi-lug breech ring is shown with one of the arms failed in the fatigue test. Multi-lug breech failures generally occur at the surface in the lower back of the front lug at 35° to 45° from normal, as shown in the upper part of the left figure. Table 1 gives the fatigue test results of four shot peened and overload breeches. Life-to-crack initiation and total fatigue life are compared for the four breeches. The cycles-to-crack initiation was determined by magnetic particle inspection. The overload technique extends both the total fatigue life and the life-to-crack initiation compared with the shot peening process.

Shot Peened Almen Strips

The shot peening process on Almen strips has been widely used to monitor the shot peening process on the actual breech. An Almen C strip measuring 3.0' x 0.745' x 0.094' after

cold working was used. The shot peening process produced an Almen arc height of 0.006' at 100% coverage on an Almen strip. Almen intensity was 0.006C. The Almen gage curvature measurement agreed with the curvature measurement at mid-point of the Almen strip using an optical camera. Surface transverse stress measurement at the mid-point of an Almen strip was -90 Ksi in the transverse direction and -92 Ksi in the longitudinal direction. However, stress relaxation already occurred when the Almen strip was removed from the shot peening process, resulting in curvature.

Technique for Measurement of Shot Peened Residual Stresses

Two position-sensitive stress analyzers were used in this analysis: a multiple-exposure TEC stress analyzer and a Denver dual-detector single-exposure system with a reticon photo-diode array, modified for multiple-exposure operation. As shown in Figure 4, shot peening residual stress analysis was performed in the vertical direction for accuracy. Angular range accessible to X-ray psi-angle rotation is shown as dotted lines where the X-ray beam spans the opening of the lugs. In cases where angles were severely limited, a horizontal cut at the upper edge of the lugs was necessary.

Residual stress depth profiles were obtained by removing successive surface material layers and making analytical corrections for residual stresses due to layer removal. Surface layers were removed by electropolishing the material inside the lugs using a Buehler Electromet III. Around 25 microns (1 mil) at a time were removed, measured by a micrometer with a pointed anvil. The etchants used were a mixture of 800-ml alcohol and 200-ml perchloric acid.

Experimental data were obtained in both the unaffected arm after fatigue experiments and the intact portion of the arm that failed. Error analysis included counting statistics error from the proportional counter, and goodness of fit of sin-sqr-psi to a line in the TEC measurements. Depending on the size of the collimator and slit used, as well as the counting rate of the given sample, measurement accuracy was around 5 Ksi. For difficult focusing conditions due to curved surfaces and limited psi angular range due to geometry, measurement accuracy was around 10-15 Ksi.

Shot peened residual stress measurement in the multi-lug breech is difficult due to the lug geometry:

- Precise focusing and measurement on a curved surface contour.
- Irregular geometry shielding X-ray and limiting the psi angular range.
- Surface material removal on a curved surface.
- Numerical corrections for stress relaxation due to layer removal.

Intensity plots were obtained to avoid possible shielding of X-rays. When it appeared that X-ray intensity might be shielded, a smaller psi range was chosen, and the run was repeated.

Shot Peened Residual Stress in the Multi-Lug Breech Ring

Shot peened residual stress depth distribution analysis was made for breech #18, which came from a breech with a failed front lug. Measurements were made in the middle and rear lugs near the bottom of the failed arm and in the front lug of the intact arm of the breech ring. Cross-sections of the specimen were 3-6 cm thick. Elastic constant for the 211 planes of A723 steel was determined using previous four-point bend calibration.[8]

Table 2 gives the surface hoop residual stresses along the length of the middle fillet using the Denver analyzer. Data were given in both MPa and Ksi. The experiment was to detect possible edge effect on the hoop stresses due to cutting of the slices. Consistent results were obtained with an average surface stress of -80 Ksi, with standard deviation of 8 Ksi in the middle lug. The errors shown in the table represent data dispersion from three repeated measurements using local-developed software control. The results indicate that edge effect is not important for shot peened specimens.

Table 3 gives residual stress distributions in the middle lug as a function of depth from the surface using the successive layer removal technique and TEC stress analyzer. The data are summarized in Figure 5. Due to the nature of the shot peening process, axial stress depth distribution in the middle lug is similar to hoop stress distribution. Hoop stresses in the rear-front lug and rear-back lug show similar magnitude and distribution. The shot peening process produces fairly uniform residual stress distribution. Shot peened breech #21, obtained from the intact portion of the arm opposite to the arm that failed, was made available only recently. Surface stress measurements were performed in the bottom of the front lug. The average stress was -92 Ksi (-644 MPa).

Layer Removal Residual Stress Corrections

Table 4 gives the calculated corrections for layer removal in shot peening measurements. The corrections are based on an algorithm in the SAE Handbook.[9] Our residual stress depth distribution and austenite/martinsite volume fraction analyses in a carburized 5120 steel specimen resulted in residual stress corrections up to 9 Ksi (62 MPa) due to layer removal.[10] In that case, up to 4 mm of depth was removed from a substrate thickness of 1 cm in a hockey puck. In the present study of the A723 steel multi-lug breech, residual stress corrections due to layer removal were small and could be ignored because the substrate is very thick compared with the thin layer removed.

Topography of Shot Peened Breech

Morphology of the shot peened surfaces was examined using an optical and electron microscope. Figure 6 (upper left) is the Leitz metallography camera photo of shot peened Almen strip #25-19, obtained using cast shots S-330 (0.84 mm or 33 mil). The surface was slightly polished to enhance contrast. The bottom left, upper right, and lower right photos are scanning

electron microscope images of surfaces of the middle lug of a multi-lug breech ring amplified 10, 50, and 100 times, respectively. Average diameter of the indentation is around 133 microns (5 mils).

Elastic/Plastic Indentation Problem

When an elastic/plastic target is impacted by hard spherical projectiles, the target material undergoes local plastic deformation with lateral stretching and grain distortion. The rest of the elastic surrounding material tends to push the plastically deformed zone. During elastic recovery, the target acquires a shallow layer of compressive stresses and smaller equilibrating tensile stresses below. Shot peening process investigations have been conducted by many researchers, including Wohlfahrt[11] and Niku-Lari.[12] Dual shot peening to maximize beneficial residual stresses has also been reported.[13] The multiple-impact problem of high-velocity hard spherical projectiles on an elastic/plastic target is very complex and has been studied by Shaw and De Salvo[14] and Khabou et al.[15] Al-Hassani[16] proposed the concepts of shakedown, reverse yielding, Bauschinger effect, and strain rate in interpreting residual stress distribution in shot peening, including surface residual stress, magnitude and location of maximum compressive stress, thickness of the yielded layer, and compensating tensile-stress distribution. A three-dimensional dynamic finite element model of shot peening was made by Al-Obaid.[17] Shot peening parameters such as shot size and velocity, impact angle, material constants, and yield strength for the shots and target must be defined before experimental residual stresses can be compared with theoretical models.

Overload Residual Stress in the Multi-Lug Ring

As shown in Figure 7, both vertical measurements of surface hoop residual stress in the lugs and horizontal measurements on the cross-section were performed for overload breech #23. The specimen was obtained from the intact portion of the arm opposite the failed arm. The cross-section surface was electropolished, and a 10 mil thickness was removed from the surface layer to avoid effects due to machine stresses, oxidation, corrosion, etc. In cross-section measurements, a hoop is defined as the direction parallel to the tangent at the lug surface. Directions AC and BC were perpendicular to the roots of the front and middle lugs. AA was in a direction perpendicular to the tangent at a point on the breech where the breech failed; AB was mid-point along the arc between AA and AC. BA in the middle lug was parallel to AA in the front lug.

Figure 8 gives the hoop stress distribution along directions AA, AB, and AC in the front lug. Maximum compressive stresses along AA, AB, and AC were -60, -100, and -110 Ksi, respectively, which translate into -420, -700, and -770 MPa. The thicknesses of the yielded layers along AA, AB, and AC were 5 mm, 7 mm, and 1 cm. Figure 9 gives the hoop stress distribution along directions BA and BC of the middle lug. Maximum compressive stresses along BA and BC were -50 and -95 Ksi (-350 and -665 MPa); the thicknesses of yielded layer were 2 mm and 4 mm.

In the front and middle lugs, the magnitude of the compressive residual stresses was highest near the bottom of the lugs, decreasing while moving up along the sides of the lugs. The thickness of the compressive layer was largest near the bottom of the lugs compared with the sides of the lugs.

SUMMARY

The present work confirmed that multi-lug breech design and effective residual stress management significantly improved the fatigue life in the EX35 multi-lug breech. Our results are summarized as follows:

- Shot peened residual stress depth distributions were fairly uniform in all lugs, while overload residual stresses depend on lug, location, and geometry.

- Shot peening and overload processes both generated compressive residual stress layers of comparable magnitude. However, the overload process produced a compressive residual stress layer an order of magnitude deeper than the shot peening process.

- Fatigue life improved by a factor of two due to the thicker compressive layer generated in the overload multi-lug breech compared with the shot peened breech.

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Table 1. Comparison of fatigue test results - shot peening vs. overload techniques

Specimen	Cycles (Initiation)	Cycles (Failure)	Treatment	Breech Type
18	12,000	14,471	Shot Peening	Upslider
20	19,000	26,534	Overload	Upslider
21	9,000	12,708	Shot Peening	Downslider
23	16,800	26,572	Overload	Downslider

Table 2. Shot peening surface hoop stresses in the middle lug as a function of axial distance along the lug

Distance from Edge (mm)	Hoop Stress (Ksi)	Error (Ksi)	Hoop Stress (MPa)	Error (MPa)
2.5	-74.9	3.3	-525	23
5.0	-81.9	5.2	-573	37
7.5	-91.2	3.9	-638	27
10.0	-97.8	3.3	-685	23
12.5	-85.9	4.7	-602	33
15.0	-95.8	4.6	-671	32
17.5	-83.4	4.4	-584	31
20.0	-72.3	3.4	-506	25
22.5	-73.6	7.1	-515	50
25.0	-74.3	4.3	-520	30
27.5	-79.3	2.6	-555	18
30.0	-74.5	5.3	-522	37
32.5	-81.8	2.1	-573	15
35.0	-72.4	4.4	-507	31
37.5	-75.1	4.7	-526	33
40.0	-76.5	4.7	-536	33
42.5	-73.9	5.5	-517	39

Table 3. Shot peening hoop residual stresses as a function of depth from the surface

Distance (mm)	Middle Lug Hoop Stress (MPa) (Ksi)	Middle Lug Axial Stress (MPa) (Ksi)	Rear Lug Front Hoop (MPa) (Ksi)	Rear Lug Back Axial (MPa) (Ksi)	Rear Lug Back Hoop (MPa) (Ksi)	Rear Lug Back Axial (MPa) (Ksi)
0.00	-533, -76.1	-700, -100.0	-502, -71.7	-601, -85.8	-571, -81.6	-748, -106.8
0.03	-669, -95.6	-512, -73.2	-555, -79.3		-771, -110.2	
0.05	-814, -116.3	-561, -80.2	-522, -74.6			
0.08	-674, -96.3	-640, -91.5	-501, -71.5		-882, -126.0	
0.10	-416, -59.4	-369, -52.7			-510, -72.9	
0.13	-175, -25.0	-95, -13.6	-547, -78.2			
0.15	-141, -20.1	-30, -04.3	-385, -55.1		-409, -58.4	
0.18			-132, -18.9			
0.20	-49, -7.0	5, 0.70				
0.25	-29, -4.2	1, 0.13	-26, -3.8		-379, -54.1	
0.38	-9, -1.3				-263, -37.5	
0.51					-197, -28.1	

Table 4. Surface layer removal correction in a shot peened multi-lug breech

Filename	Polish Depth (in.)	Raw Stress (Ksi)	Corrected Stress (Ksi)
54220.SPC	0.000	-76.1	-76.1
005433.SPC	0.001	-95.6	-95.2
005436.SPC	0.002	-116.3	-115.5
54370A.SPC	0.003	-96.3	-95.2
005440.SPC	0.004	-59.4	-58.5
54410B.SPC	0.005	-25.0	-24.5
005444.SPC	0.006	-20.1	-19.6
005445.SPC	0.008	-7.0	-6.8
005448.SPC	0.010	-4.2	-4.0
005449.SPC	0.015	-1.3	-1.2

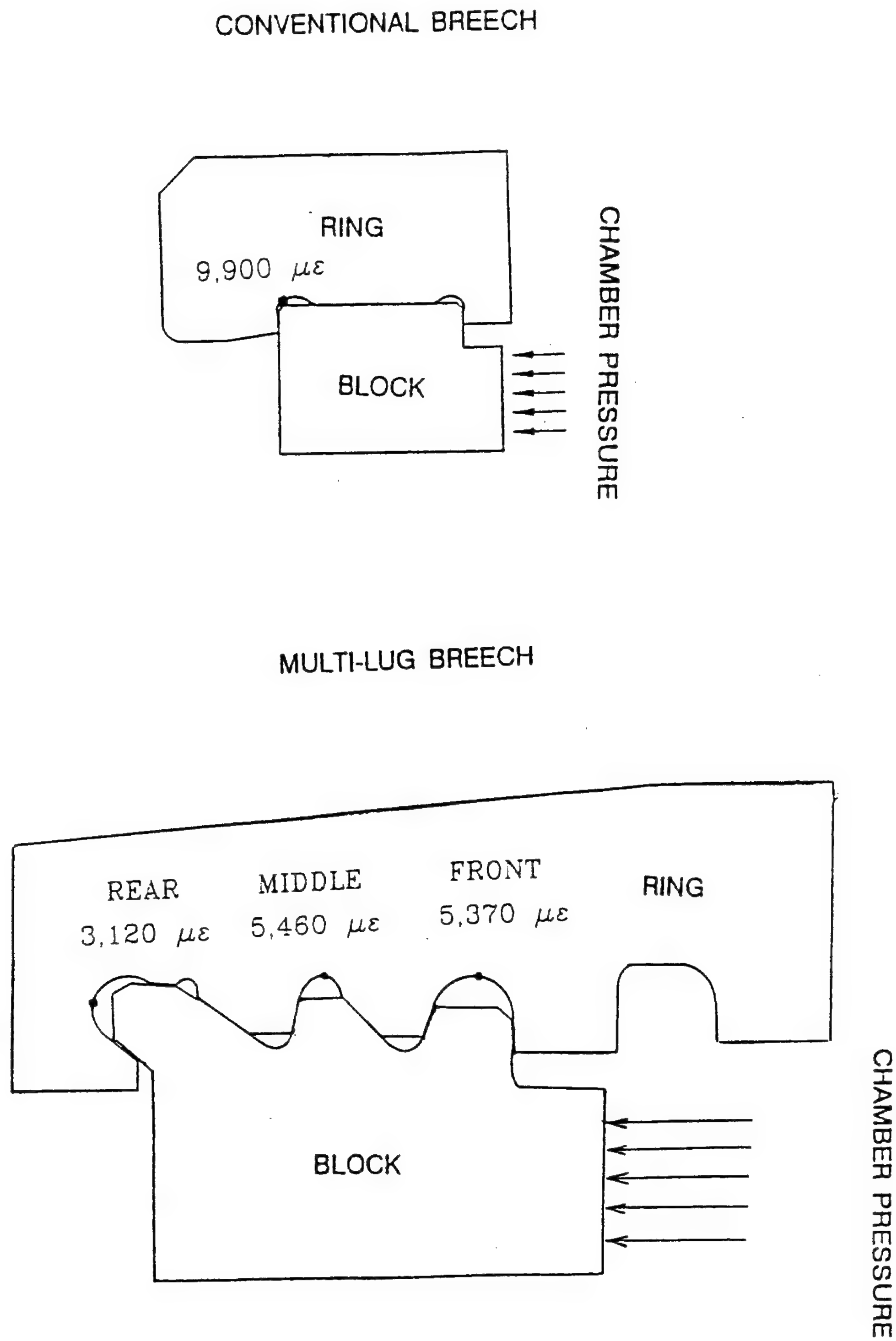

Figure 1. Cross-section of conventional breech and multi-lug breech showing direction of chamber pressure. (Note that the rear lug in the multi-lug breech consists of two components.)

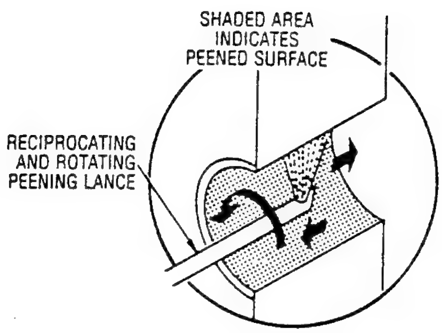

Figure 2. Inside diameter shot peening technique applied to surfaces in the lugs of a multi-lug breech ring using a peening nozzle

FATIGUE TEST FAILED MULTI-LUG BREECH RING

SHOT PEENING AND OVERLOAD PROCESSES HAVE BEEN CONSIDERED TO INDUCE ADVANTAGEOUS RESIDUAL STRESSES IN THE MULTI-LUG BREECH RING IN ORDER TO COUNTER THE HIGH TENSILE STRAINS DURING OPERATION.

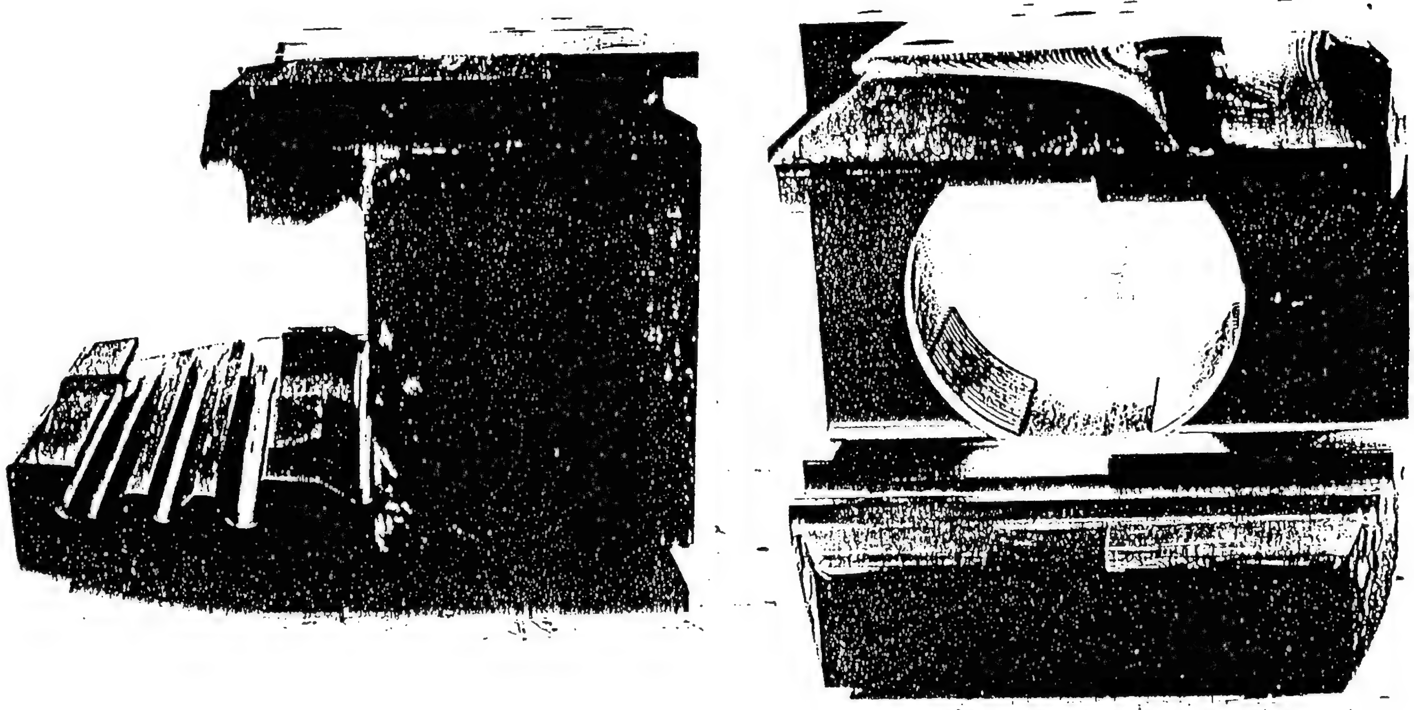

Figure 3. Fatigue test failed multi-lug breech ring. (The upper part of the left graph shows the position of failure that generally occurs at the lower back of the front lug at 35-45° from normal to the bottom of the lug.)

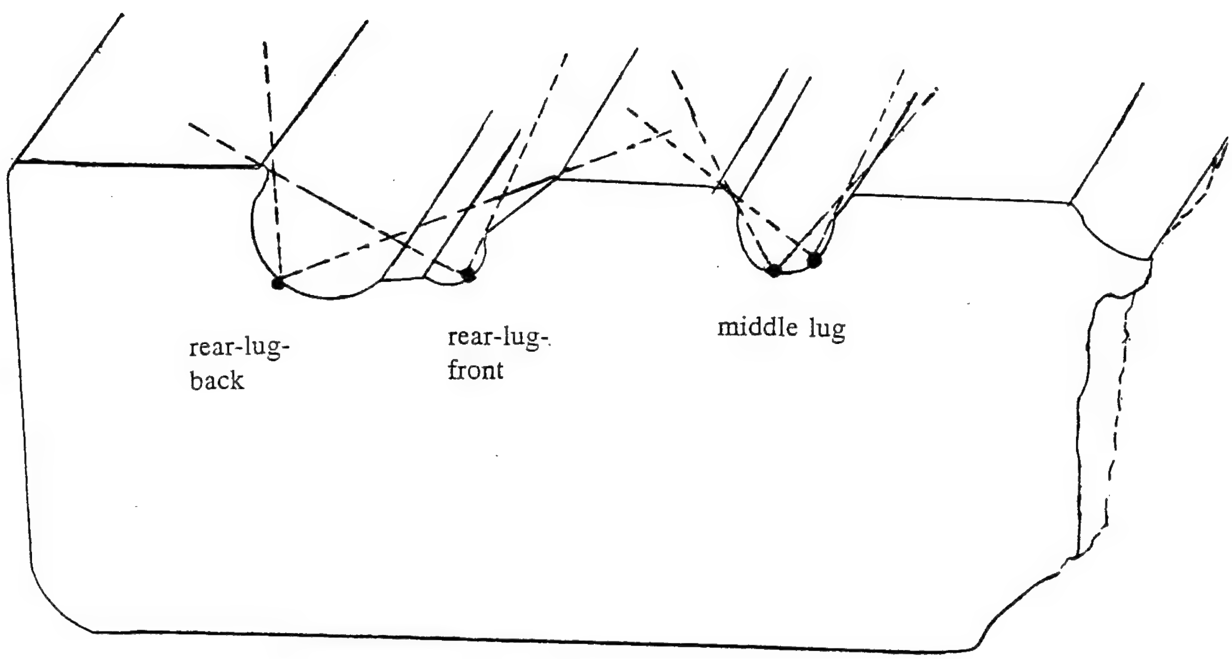

Figure 4. Example of X-ray residual stress analysis of the unaffected portion of a failed shot peened specimen, showing the angles accessible to X-ray radiation

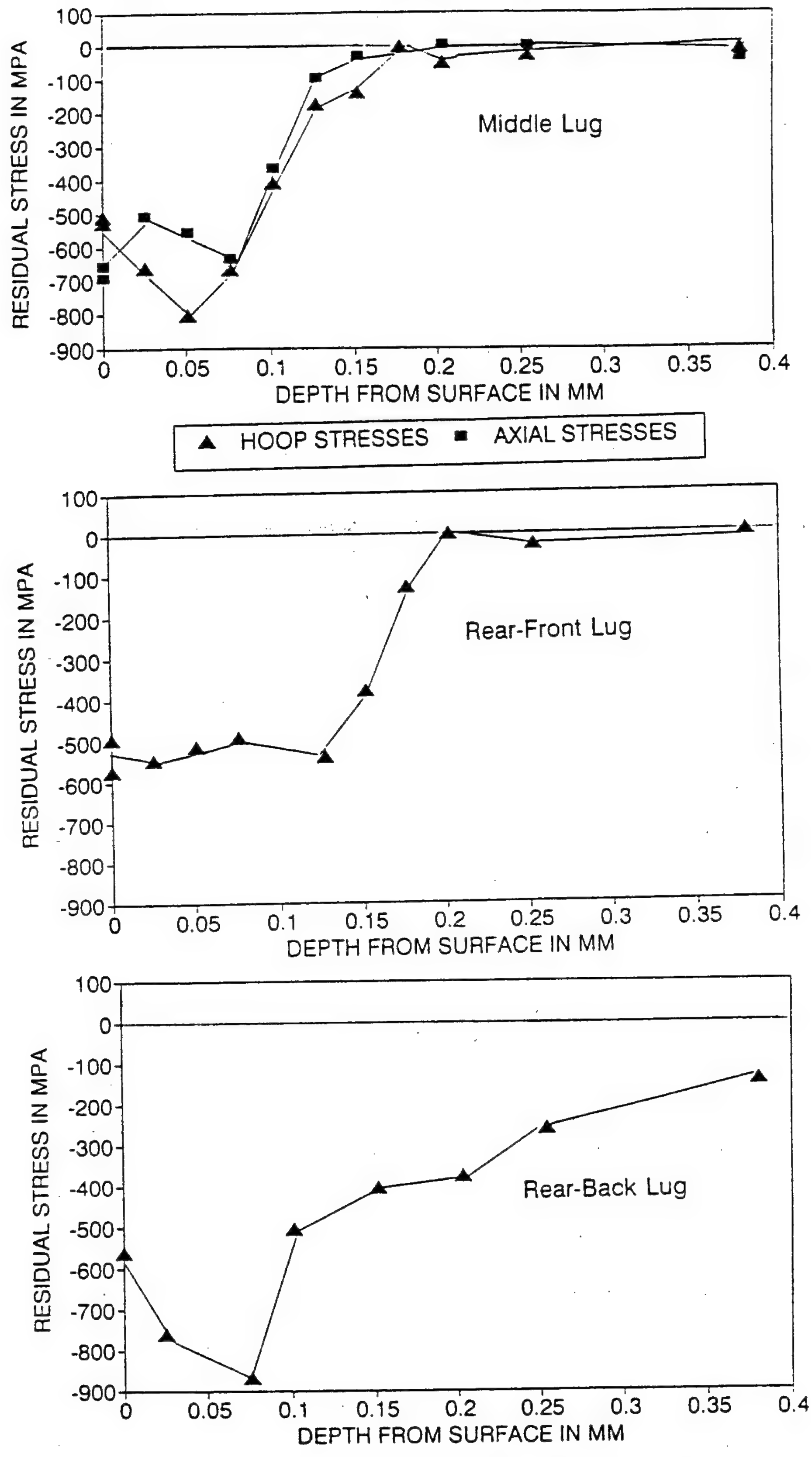

Figure 5. Shot peening residual stresses in the middle, rear-front, and rear-back lugs of a multi-lug breech ring as a function of depth from surface

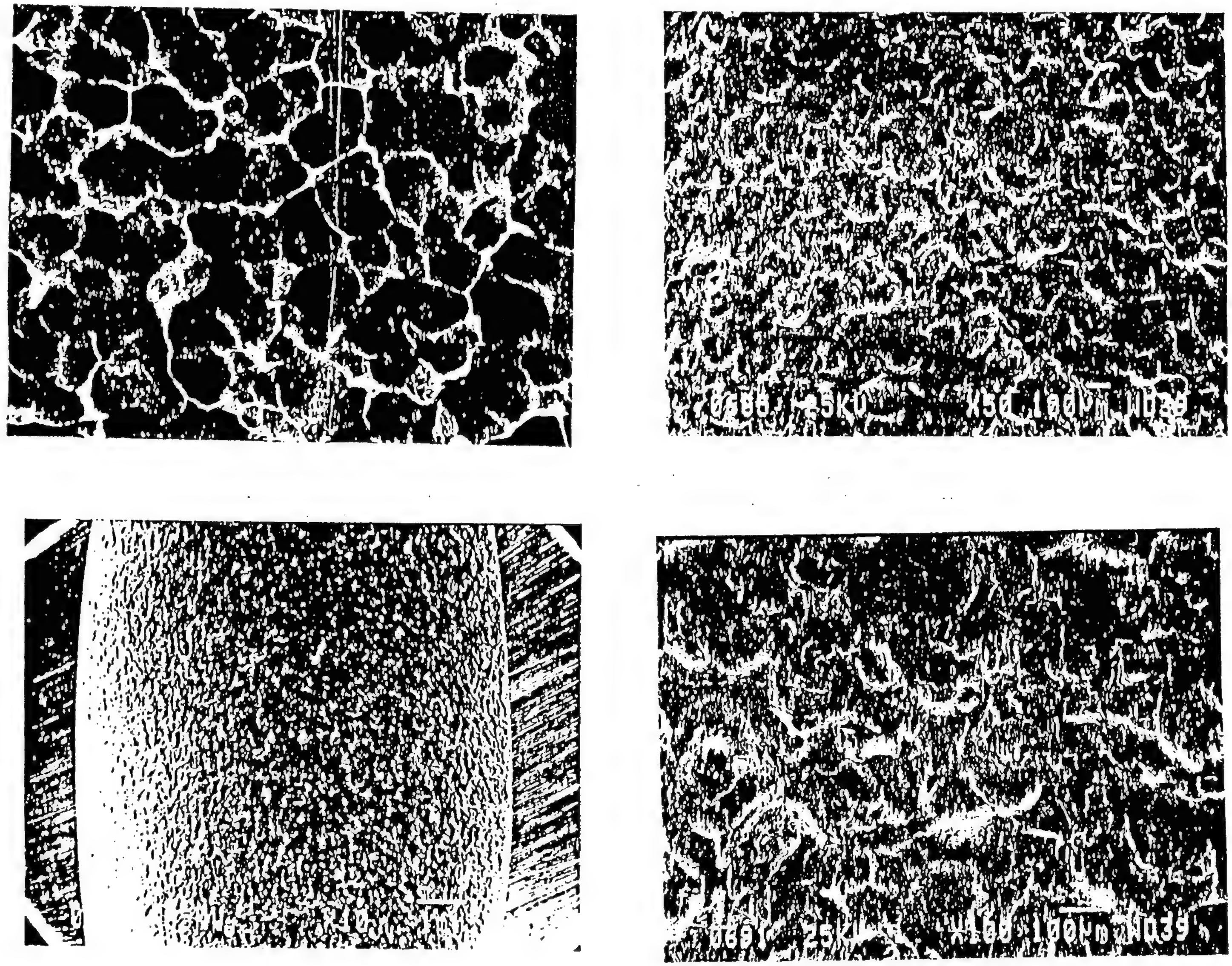

Figure 6. Topography of shot-peened surfaces (Left top is polished peened Almen strip using Leitz metallography camera. Left bottom (x10), right top (x50), right bottom (x100) scanning electron microscope images of peened EX35 multi-lug breech ring.)

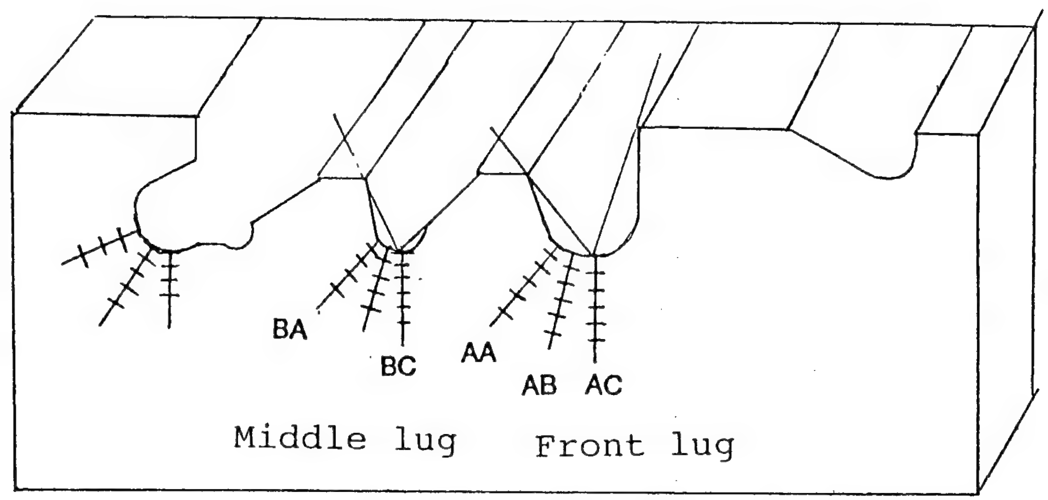

Figure 7. Overload residual stress analysis in the lugs of a multi-lug breech ring

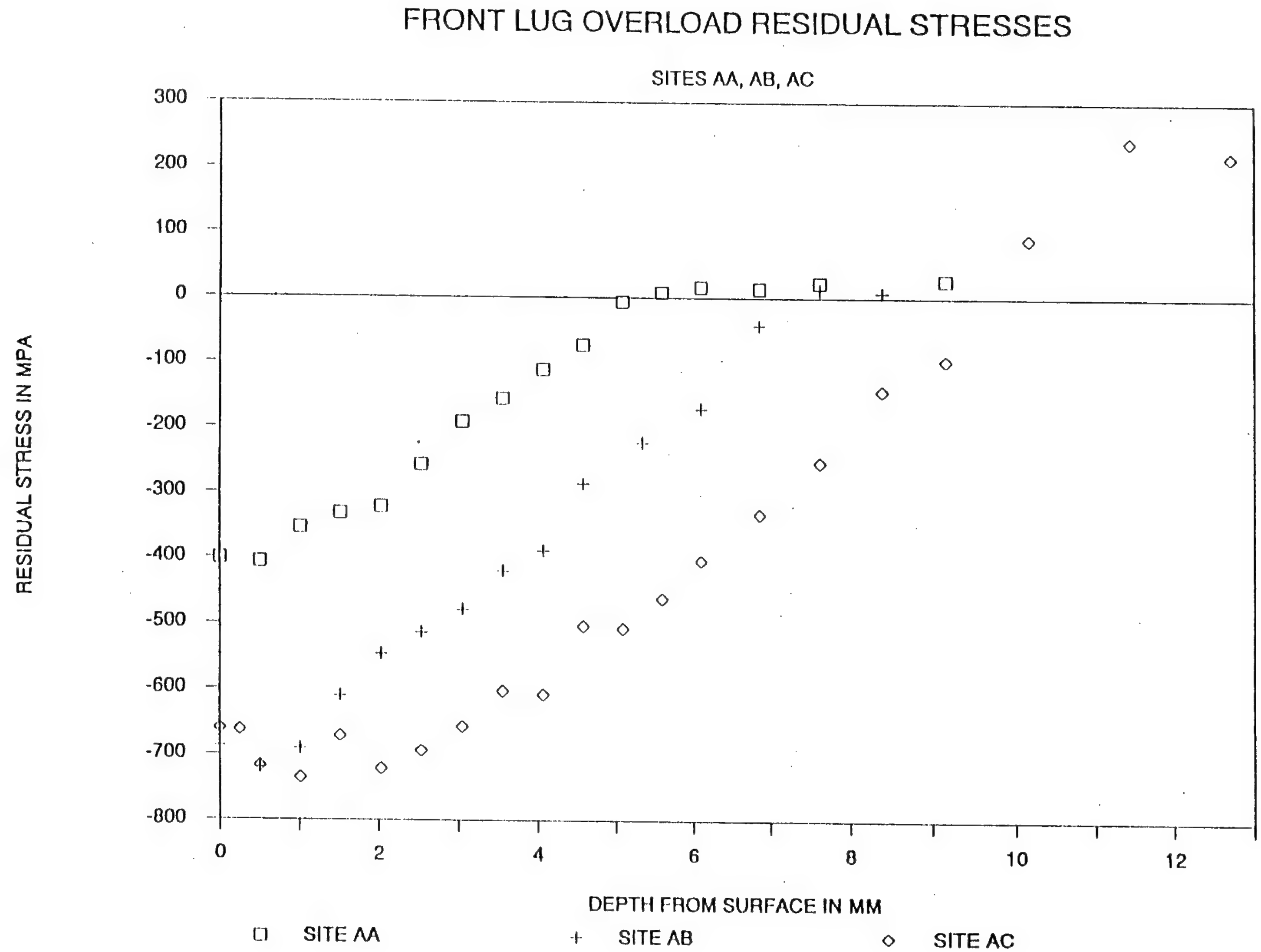

Figure 8. Front lug overload hoop residual stresses as a function of depth from the surface

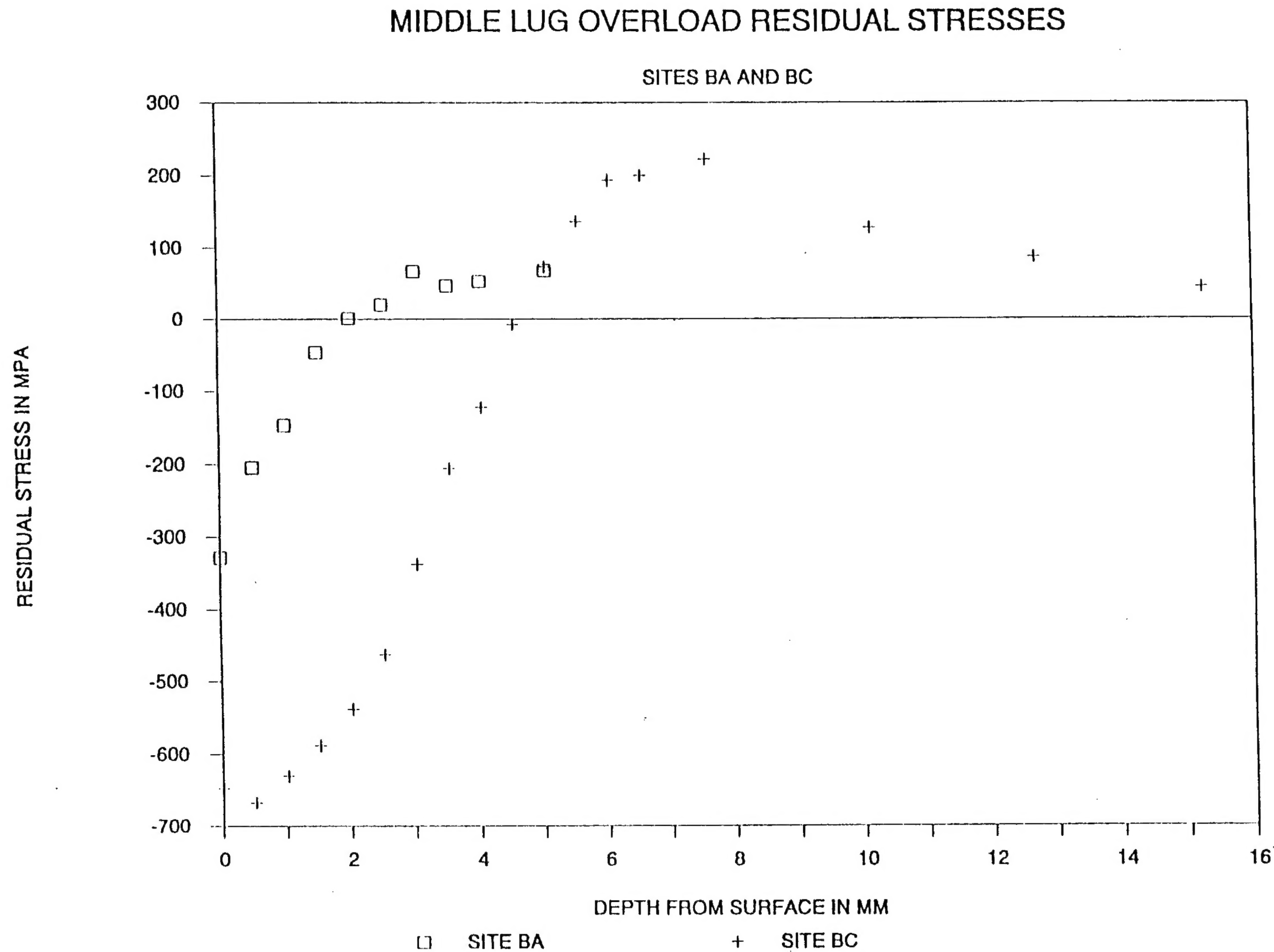

Figure 9. Middle lug overload hoop residual stresses as a function of depth from the surface

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